International Journal of GEOMATE, April, 2024 Vol.26, Issue 116, pp.19-26
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2024.116.4262
Geotechnique, Construction Materials and Environment

COMPACTION PROPERTIES OF THE FLY-ASH BASED GEOPOLYMER ON SILT SOIL

*Edi Hartono[1], Willis Diana[1], Yogi Surya Nugraha[1], and Muhamad Afzalurrahman [1]

[1]Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Indonesia

*Corresponding Author, Received: 15 Nov. 2023, Revised: 05 Feb. 2024, Accepted: 25 Feb. 2024

ABSTRACT: This study investigates the effect of varying the alkali ratio and the molarity of NaOH on the compaction properties of silt stabilized with fly ash-based geopolymers. Geopolymers offer an ecologically sound alternative to traditional cementitious materials and show promise in soil stabilization applications. Fly ash is a frequently utilized precursor in producing geopolymers. Although the benefits of utilizing fly ash as a precursor for geopolymer creation and its potential for stabilizing soil have been recognized, there has been insufficient exploration into refining alkali ratios and NaOH molarities to obtain the desired compaction characteristics. This study examines the compaction characteristics of stabilized silt soil by studying the effects of alkali ratio and NaOH molarity. The standard Proctor compaction test has determined the optimum moisture content (OMC) and maximum dry density (MDD). The results indicate that the utilization of fly ash geopolymer stabilization can improve the compaction characteristics of soil by increasing its MDD and decreasing its OMC. The observed MDD reached its highest value of 16.23 kN/m^3. The fly ash geopolymer stabilization MDD was reached with 14 molars of sodium hydroxide and a ratio of 2 for the alkali activator. The OMC value of 9.12% was also reached in the same conditions. The alkali ratio and NaOH molarity had a significant impact on the compaction parameters of geopolymer-stabilized silt soil. Understanding the impact of these factors is crucial for the success of soil stabilization projects.

Keywords: Compaction, Maximum dry density, Optimum moisture content, Geopolymers, Fly ash, Alkaline activator

1. INTRODUCTION

Compaction is the process of rearranging soil particles against resistance under the force of the compaction energy, which decreases the void space in the soil and increases its density [1][2]. Soil compaction is influenced by various factors, including soil composition, the surface morphology of soil particles, and moisture content [3, 4]. The alteration in soil density during the compaction process is influenced by two factors: the direct compression of the void space between soil particles and the reduction of void space caused by movements in the positions and orientations of the soil particles. Water functions as a lubricant in this process, and the ideal density occurs when the interstitial spaces between soil particles are saturated with water. Due to the gravitational attraction between the particles, soil can retain a loose compacted structure when water is low. Most of the pores within the unsaturated zone exhibit interconnectivity and contain a higher proportion of air relative to water [5]. Low moisture content in loose soil can result in limited film lubrication of the firmly bound water developing on the surface of the soil particles at some external pressures [6] and insignificant relative motion between the soil particles, which can cause inadequate compaction. Furthermore, the gravitational tension between the soil particles hinders their movement, leading to inadequate soil compaction [7]. Nevertheless, when the water content progressively rises, the thickness of the water film on the particles' surface also increases. The amount of lubricant between soil particles likewise rises in line with this. Consequently, there is a reduction in inter-particle friction, facilitating the mobility of soil particles and augmenting the compaction effects. As the moisture content of the soil increases, there is a steady increase in the presence of unbound water, leading to an expansion of the soil's pore volume and a corresponding reduction in its dry density [8, 9]. Hence, the optimum moisture content (OMC) is defined as the minimal quantity necessary to create a water film on the soil particles' surfaces, providing enough support for the particles to undergo sliding motion. Achieving the maximum theoretical density of soil involves compressing it to a point when all the voids within the soil are completely saturated, resulting in the expulsion of all gases present. The saturation curve, the theoretically achievable maximum compaction curve, can be derived by plotting the moisture contents against the equivalent dry densities of soil at saturation [10]. The particle size distribution has a significant impact on the maximum dry density (MDD) and optimum moisture content (OMC) [11]. In a study conducted by Hassan [12], it was determined that the most significant relationships are those between maximum dry density and the percentage of fines (silt and sand), as well as the relationship between optimum moisture content and the percentage of fines. According to the study, well-graded soils have superior dry densities than poorly graded soils when the acceptable content of both soils is equal, and plastic particles tend to raise the maximum dry densities.

Geopolymer is an inorganic aluminosilicate substance that is synthesized via the polycondensation process of tetrahedral silica (SiO4) and alumina (AlO4). These two components are connected alternatingly by mutually sharing all oxygen atoms [13]. Any substance that contains pozzolanic compounds or provides a source of silica and alumina, which may be easily dissolved in an alkaline solution, serves as a precursor for geopolymer species and facilitates the process of geopolymerization [14]. The activator used in this context is a chemical derived from an element found in the first group of the periodic table. Consequently, this substance is commonly called alkali-activated aluminosilicate binders or alkali-activated cementitious material [14]. The chemical reaction between silica and alumina atoms produces molecules that are structurally and chemically similar to the components of naturally occurring rocks [14]. The inorganic polymeric substance can be regarded as an amorphous counterpart to geological feldspars, albeit produced using a process akin to the synthesis of thermosetting organic polymers. Hence, these materials are called "geopolymers" [15]. The process of geopolymerization can be described as a series of interconnected steps. Firstly, amorphous aluminosilicate materials are dissolved by either an alkali hydroxide or alkaline silicate solution. This dissolution results in the formation of reactive silica and alumina. Secondly, the dissolved species undergo polycondensation, leading to the formation of amorphous or semi-crystalline oligomers. These oligomers further polymerize and solidify, ultimately forming synthetic aluminosilicate materials [14]. The main prerequisites for geopolymerization are materials rich in Si (such as fly ash, slag, and rice husk) and materials rich in Al (clays such as kaolin, bentonites) [14]. The effective creation of a binding gel on geopolymerization soil stabilization, which enhances the compaction of particles and improves the mechanical characteristics [16] and volume stability of soils, is confirmed using microstructural characterization techniques such as scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FT-IR) [17].

Based on prior research, the use of fly ash geopolymer for soil stabilization yields variable results, depending on the type of soil and its minerals, the content and type of precursor and activator, the molarity of alkali activator, alkali activator ratio, curing time, and treatment conditions [18]. Several researchers have studied using geopolymers as a soil stabilization material, yielding findings that indicate similarities between geopolymers and cement. These similarities include enhancing shear strength, strength, stiffness, and shrinkage and exhibiting favorable characteristics such as good acid resistance, fire resistance, and sound density characteristics [13, 19-26]. The presence of an excessive quantity of alkaline activator solution leads to a proportional increase in the quantity of geopolymer present in the sample. Various research has addressed this matter and examined the efficacy of alkaline activation (AA) in soil stabilization [22, 27, 28]. The results on compressive strength can vary depending on the alkali ratio (Na2SiO3/NaOH) applied to the specimens. The geopolymerization process is influenced by the ratio of the alkaline solution, with particular emphasis on the silica (Si) compound. This compound is crucial in forming a more enhanced material matrix [29]. However, a specific ratio may have a detrimental effect on the overall performance of the geopolymer material. Applying the Scanning Electron Microscopy (SEM) technique for testing materials with an alkaline ratio (Na_2SiO_3/NaOH) of 1.5 reveals a more compact arrangement than higher ratios. The presence of Na_2SiO_3 in an alkali solution contributes to the uniformity of geopolymer formation, whereas an excessive quantity of Na_2SiO_3 can impede the process of geopolymerization [30]. The imperfect cementation process caused by the suppression of geopolymerization leads to a decrease in the strength of the geopolymer-stabilized material. The geopolymerization process is affected not only by the alkali ratio but also by the curing age. This finding aligns with the research conducted by Ramya and Jeyapriya [30], which suggests that the strength of the specimen depends on how the geopolymerization process takes place. Increasing the length of the curing procedure provides more time for the geopolymerization process to strengthen the bonding of the material [20].

The compaction of soil has a significant role in determining its geotechnical qualities and overall stability, particularly when soil stabilization is achieved through applying fly ash-based geopolymer [31]. The compaction characteristics of mixtures comprising soil and fly ash have been investigated, revealing that including fly ash in the soil can enhance its compressibility behavior and swelling qualities [32][33]. The compaction experiments can be utilized to establish the optimal moisture content and maximum dry density of soil-fly ash combinations [34]. The fly ash particles and cementitious products in the treated soil are thought to act as nucleation sites to bind the soil into a more solid structure [35]. Due to its impact on the soil's compressibility behavior, swelling characteristics, and shear strength, compaction is essential to creating fly ash geopolymer-stabilized soil. The compaction qualities of soil were shown to be improved by the addition of fly ash [36]. The dry unit weight of the soil exhibited an upward trend as the fly ash concentration rose, reaching a peak at a specific percentage. Subsequently, the dry unit weight declined [37][38]. The research study determined that the most effective fly ash content for compaction was approximately 20% [39]. The study by Kumar et al. [40] examined the impact of sodium hydroxide on the optimum moisture content of soil and geopolymer materials. An investigation found that the effective concentration of sodium hydroxide for lowering the optimum moisture content of the soil is 6%. The density of the paste rises with an increase in NaOH molarity from 8 M to 10 M, according to a study on geopolymer paste [41].

While several research investigations have examined the alterations in material characteristics before or during stabilization, optimum composition of material stabilization to get the maximum strength [40], limited studies have been made to utilize these soil attributes to predict Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) [41]. Geopolymer fly-ash soil compaction testing was infrequently done in several past research [15]. The standard Proctor density test is commonly conducted on untreated soil to ascertain the density of geopolymer fly ash-soil specimens that will be subjected to strength testing. The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the untreated soil are employed to assess the density and moisture content of the geopolymer fly ash soil.

The present study examines the compaction properties (MDD and OMC) of fine-grained soil mixtures, specifically silt, treated with a geopolymer based on fly ash. The alkali activators employed in this study consist of sodium hydroxide and sodium silicate, utilized in different proportions and subjected to variations in sodium hydroxide concentration.

2. RESEARCH SIGNIFICANCE

When the soil is combined with the precursor and alkali activator, the initial geopolymerization reaction occurs promptly, rapidly altering the plasticity of the fine-grained soil. In turn, this leads to modifications in the compaction characteristics, explicitly affecting the MDD and OMC. To achieve optimal compaction in chemical stabilization, it is necessary to determine the OMC of the soil being compacted, at which the MDD is attained. However, many studies conducted on fly ash geopolymer-stabilized soil have primarily concentrated on enhancing strength [42] [43] and durability, while insufficiently addressing the compaction behavior characteristics. Therefore, the compaction behavior of silt soil stabilized by fly ash geopolymer will be the focus of this study.

3. MATERIAL AND METHODS

The present study used low-plasticity silt soil, characterized ML soil. This disturbed soil was obtained in Seyegan District, Sleman Regency, and Special Region of Yogyakarta. Table 1 presents a comprehensive summary of the physical and mechanical data of the soil.

Table 1 Geotechnical properties of soil sample

Parameters	Properties
Specific gravity, G_s	2.66
Atterberg limits:	
Liquid limit, LL (%)	38.12
Plastic limit, PL (%)	35.7
Plasticity index, PI (%)	2.43
Particle-size distribution:	
Clay (%)	9.93
Silt (%)	47.14
Sand (%)	42.93
Maximum dry density, MDD (kN/m^3)	15.85
Optimum moisture content, OMC (%)	23,92
USCS classification	ML

The geopolymer utilized in this study consisted of fly ash and a sodium-based activator. The Tanjung Jati Jepara Power Plant fly ash that used in this study exhibits a low calcium content (type F fly ash). This variety of fly ash is abundant in aluminosilicate substances and is widely recognized as one of the most often employed constituents in geopolymer formulations. As recommended by numerous researchers, an alkaline activator made of sodium silicate (Na2SiO3) and sodium hydroxide (NaOH) was used. Initially, in pellet form, the sodium hydroxide was solubilized in deionized water to achieve 12, 14, and 16 molars concentrations. It was left undisturbed for at least 24 hours before combining with the sodium silicate. The alkali activator ratio, also known as the weight ratio of sodium hydroxide to sodium silicate, was varied across four different values: 1, 1.5, 2, and 2.5. According to the recommendations made by previous researchers in the field, the fly-ash content used in the study was fixed at 20%.

The soil dried in the oven is crushed into fine particles to ensure it can pass through a sieve with a mesh size of 4. The fly ash is dried in an oven at a temperature of 105°C for approximately 24 hours. The substance is subsequently pulverized to achieve a particle size that can pass through a sieve with a mesh size of 200. The process involves the combination of soil and fly ash, followed by adding a liquid alkali activator. The mixture is manually blended until a uniform color is achieved, with mixing taking place for around 10 minutes. The soil-fly ash-liquid alkali activator mixture was subjected to a 24-hour rest before compaction. The compaction process followed the Proctor standard and adhered to the guidelines outlined in ASTM procedure ASTM D698 [44].

4. RESULT AND DISCUSSION

Determining the maximum dry density (MDD) and optimum moisture content (OMC) of treated soils is crucial in assessing their compaction qualities since these parameters play a significant role in field quality assurance and management. The compaction test results for both untreated soil in Fig. 1 and treated silt soils are presented in Fig. 2 and Fig. 3. Silt soils treated with fly ash-based geopolymer often exhibit slightly higher MDD (maximum dry density) values at an alkali activator ratio of 2 than untreated silt soils at an Alkali Activator Ratio of 1 and 1,5. This increase in MDD is accompanied by a decrease in the optimum moisture content (OMC) of the treated soils, which becomes more pronounced as the concentration of sodium hydroxide (NaOH) in the geopolymer increases.

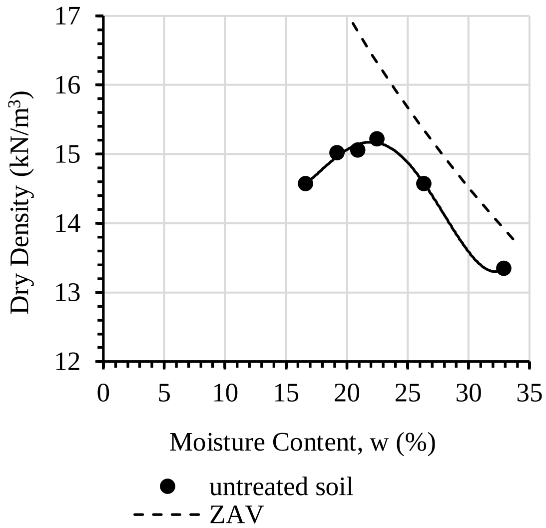

Fig.1 Compaction Curve of Untreated Soil

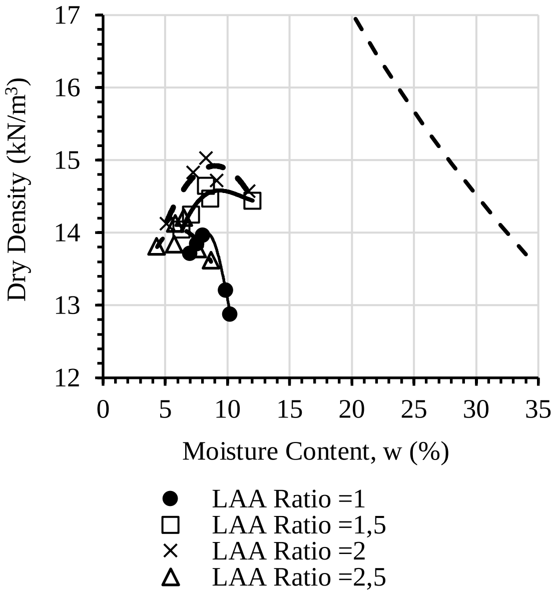

Fig.2 Compaction Curve of 12 Molars Treated Geopolymer Fly-ash Soil

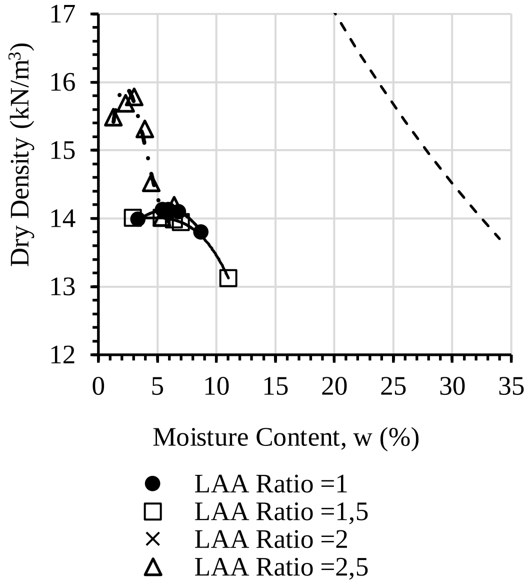

Fig.3 Compaction Curve of 14 Molars Treated Geopolymer Fly-ash Soil

The observed phenomenon can be ascribed to the chemical activators employed in the geopolymer blend, which function as lubricants [45], diminishing repulsive forces and augmenting the interparticle sliding of the silt particles. The introduction of the activator can result in lubrication, which in turn may decrease the amount of free water needed to achieve the optimal compaction, hence reducing the optimum moisture content (OMC). Furthermore, due of the insertion of chemicals (fly ash) during the treatment process, silt is partially substituted with these additives. Hence, the inclusion of these additives in the geopolymer could result in a reduction in the total surface area of the fly-ash particles possessing silty characteristics, thereby decreasing the need for liquid water.

Fig. 4 and Fig. 5 illustrate the relationship between the MDD (maximum dry density) and OMC of the soil compaction results and the fluctuations in NaOH concentration and alkali activator ratio. Tables 6 and 7 show the relationship between normalized MDD and normalized OMC to alkali activator ratio. Normalized MDD is the ratio between MDD from standard compaction of soil stabilized with fly ash geopolymer and MDD and from compaction of untreated soil. The same definition is also intended for Normalized OMC

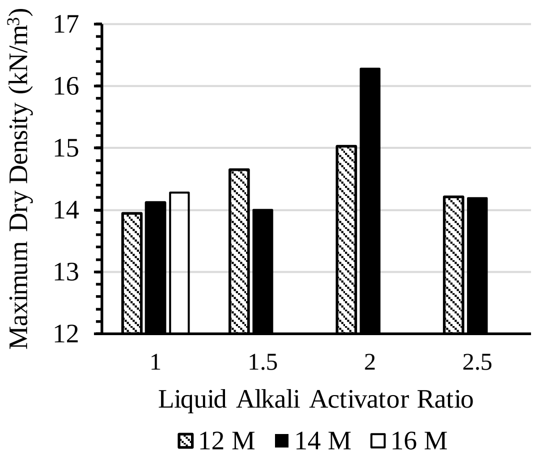

Fig.4 The Maximum Dry Density of the specimen on NaOH concentration and Ratio Alkali activator.

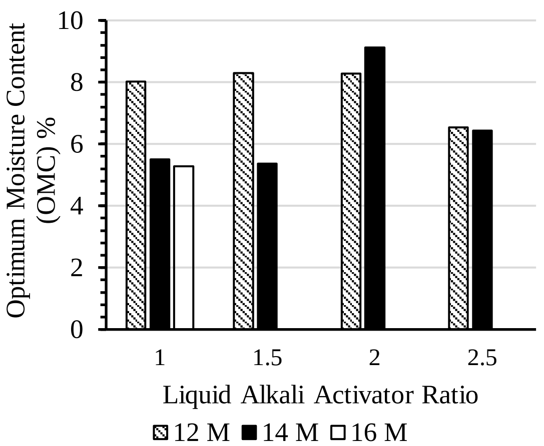

Fig.5 The Optimum Moisture Content of the specimen on NaOH concentration and Ratio Alkali activator

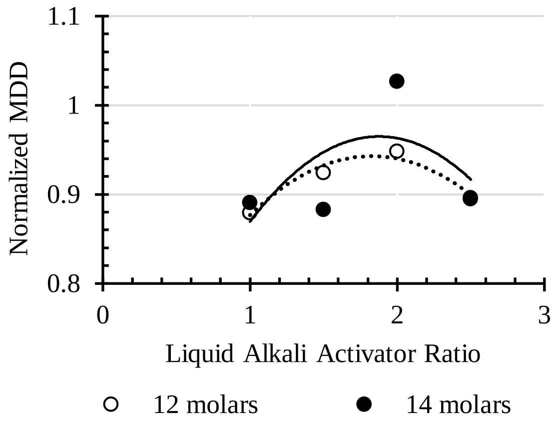

Fig.6 The Relationship of Normalized Maximum Dry Density (MDD) and Ratio Alkali activator.

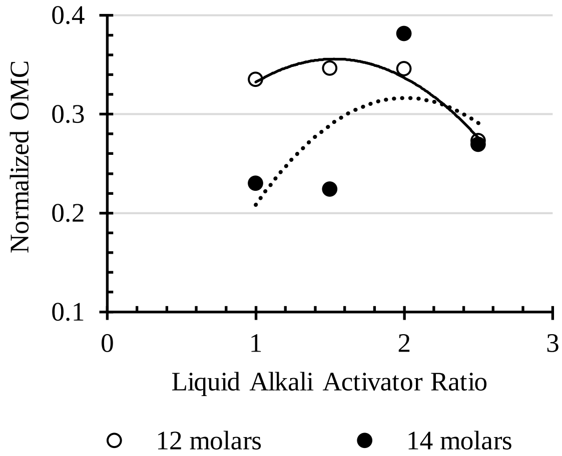

Fig.7 The Relationship of Normalized Optimum Moisture Content (OMC) and Ratio Alkali activator.

Based on the data presented in the Fig 4 to Fig 7, it was determined that the highest maximum dry density (MDD) observed was 16.23 kN/m^3. This MDD value was achieved when the sodium hydroxide concentration was 14 molars, and the alkali activator ratio was 2. The OMC value of 9.12% was achieved at this specific concentration of sodium hydroxide and alkali activator. At an alkali activator ratio of 1, an increase in the concentration of sodium hydroxide from 12 molar to 16 molar leads to an increase in the maximum dry density (MDD) and a decrease in the optimum moisture content (OMC). According to Gu [46], the decrease in modulus (ratio between sodium silicate to sodium sulphate) and increase in Baume degree (density of liquid/ sodium sulphate concentration) of result in an increase in the concentration of soluble silicate $Na_2O{\cdot}mSiO_2$ in sodium sulphate. Consequently, the ion concentration in the solution increases, leading to a thinner of the diffusion layer and a reduction in the soil particles' ability to bind water. The alkali resistance of soil particles exhibits a decline, resulting in ease of compaction and subsequent reduction in the flexibility of compacted soil. This decrease in plasticity is accompanied by a decrease in the ideal moisture content and a simultaneous increase in the maximum dry density. The significance of the modulus of sodium silicate, in comparison to the Baume degree, arises from the fact that the lowering of the sodium silicate modulus is accomplished through the addition of NaOH. Sodium hydroxide (NaOH) undergoes a reaction with sodium silicate. Both the Na_2O product and the H_2O by-product could decrease the modulus and Baume degree, respectively. Hence, the impact of sodium silicate modulus on the compaction properties of loess is of greater significance. Liquid limit, plasticity index, percentage of clay content, and percentage of sand content all enhance or decrease the MDD and OMC, respectively, demonstrating the strong negative association between the two [47].

5. CONCLUSION

The highest maximum dry density (MDD) observed was 16.23 kN/m^3. This MDD value was achieved when the sodium hydroxide concentration was 14 molars, and the alkali activator ratio was 2. The OMC value of 9.12% was achieved at this specific concentration of sodium hydroxide and alkali activator. In general, increasing the concentration of NaOH resulted in an increase in the MDD and a decrease in the OMC. The solution experiences an increase in ion concentration, which causes the diffusion layer to become thinner and reduces the soil particles' capacity to retain water. Consequently, the soil particles' resistance to alkali weakens, making it easier for the soil to compact and reducing the flexibility of the compacted soil. This decrease in plasticity is accompanied by a reduction in the optimum moisture content and a simultaneous increase in the maximum dry density.

6. ACKNOWLEDGMENTS

Financial support from the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia through the Fundamental Research Grant with contract number 181/E5/PG.02.00.PL/2023 is acknowledged with gratitude.

7. REFERENCES

[1] Wu J.N., Yang P., Li, and Yang C., Influence of Moisture Content and Dry Density on the Compressibility of Disturbed Loess: A Case Study in Yan'an City, China, Sustainability, vol. 15, no. 7, 2023, p. 6212.

[2] Tiongson J. M. and Adajar M. A. Q., Compaction characteristics of a fine-grained soil potential for landfill liner application, GEOMATE Journal, vol. 19, no. 71, 2020, pp. 211-218.

[3] Benson C. H. and Daniel D.E., Influence of clods on the hydraulic conductivity of compacted clay, Journal of Geotechnical Engineering, vol. 116, no. 8, 1990, pp. 1231-1248.

[4] Otálvaro I.F., Neto M. P. C., and Caicedo B., Compressibility and microstructure of compacted laterites, Transportation Geotechnics, vol. 5, 2015, pp. 20-34.

[5] Barr A., Clarke S., Tyas A., and Warren J., Effect of moisture content on high strain rate compressibility and particle breakage in loose sand, Experimental Mechanics, vol. 58, 2018, pp. 1331-1334.

[6] Akagi H., A physico-chemical approach to the consolidation mechanism of soft clays, Soils and foundations, vol. 34, no. 4, 1994, pp. 43-50.

[7] Duan X., Mechanical effects of solid water on the particle skeleton of soil: mechanism analysis, Geofluids, vol. 2021, 2021, pp. 1-11.

[8] Yu M., Peng X., and Fang Z., Water morphologies and distribution in wet soil and sands, in International Conference on Micro/Nanoscale Heat Transfer, vol. 42924, 2008, pp. 881-887.

[9] Xu P., Zhang Q., Qian H., Li M., and Yang F., An investigation into the relationship between saturated permeability and microstructure of remolded loess: a case study from Chinese Loess Plateau, Geoderma, vol. 382, 2021, p. 114774.

[10] Ren X.-C., Lai Y.-M., Zhang F.-Y., and Hu K., Test method for determination of optimum moisture content of soil and maximum dry density, KSCE Journal of Civil Engineering, vol. 19, 2015, pp. 2061-2066.

[11] Etim U.B., and Ehilegbu J, Critical moisture content, bulk density relationships and compaction of cultivated and uncultivated soils in the humid tropics, Asian Soil Research Journal, vol. 1, no. 2, 2018, pp. 1-9.

[12] Hassan W., Ahmad, M.A., Farooq, A.A., Ali H. Q., and Ilyas Y., Correlation of maximum laboratory dry density and optimum moisture content of soil with soil parameters, NFC IEFR Journal of Engineering and Scientific Research, vol. 5, 2017, pp. 1-6.

[13] Zhang M., Guo H., El-Korchi T., Zhang G., and Tao M., Experimental feasibility study of geopolymer as the next-generation soil stabilizer, Construction and building materials, vol. 47, 2013, pp. 1468-1478.

[14] Khale D., and Chaudhary R., Mechanism of geopolymerization and factors influencing its development: a review, Journal of materials science, vol. 42, 2007, pp. 729-746.

[15] Hos, J., McCormick P., and Byrne L., Investigation of a synthetic aluminosilicate inorganic polymer, Journal of Materials Science, vol. 37, 2002, pp. 2311-2316.

[16] Diana W., Wardhani W.I., Muntohar A.S., and Hartono E., The unconfined compressive strength of fly-ash geopolymer-stabilized sand, in AIP Conference Proceedings, vol. 2846, no. 1: AIP Publishing, 2023, pp. 1-6.

[17] Sharma K., and Kumar A., Utilization of industrial waste—based geopolymers as a soil stabilizer—a review, Innovative Infrastructure Solutions, vol. 5, 2020, pp. 1-20.

[18] Cristelo N., Glendinning S., Fernandes L., and Pinto A.T., Effects of alkaline-activated fly ash and Portland cement on soft soil stabilisation, Acta Geotechnica, vol. 8, 2013, pp. 395-405.

[19] Lemougna P.N., Madi A.B., Kamseu E., Melo U.C., Delplancke M.-P., and Rahier H., Influence of the processing temperature on the compressive strength of Na activated lateritic soil for building applications, Construction and Building Materials, vol. 65, 2014, pp. 60-66.

[20] Kaur M., Singh J., and Kaur M., Synthesis of fly ash based geopolymer mortar considering different concentrations and combinations of alkaline activator solution, Ceramics International, vol. 44, no. 2, 2018, pp. 1534-1537.

[21] Kumarappa D.B., and Peethamparan S., Stress-strain characteristics and brittleness index of alkali-activated slag and class C fly ash mortars, *Journal of* Building Engineering, vol. 32, 2020, p. 101595.

[22] Cristelo N., Glendinning S., Fernandes L., and Pinto A.T., Effect of calcium content on soil stabilisation with alkaline activation, Construction and Building Materials, vol. 29, 2012, pp. 167-174.

[23] Rios S., Ramos C., Viana da Fonseca A., Cruz N., and Rodrigues C., Mechanical and durability properties of a soil stabilised with an alkali-activated cement, European Journal of Environmental and Civil Engineering, vol. 23, no. 2, 2019, pp. 245-267.

[24] Deb P. S., Nath P., and Sarker P. K., The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature, Materials & Design (1980-2015), vol. 62, 2014, pp. 32-39.

[25] Iyengar S. R., Masad E., Rodriguez A. K., Bazzi H. S., Little D., and Hanley H. J., Pavement subgrade stabilization using polymers: characterization and performance, Journal of Materials in Civil Engineering, vol. 25, no. 4, 2013, pp. 472-483.

[26] Dungca J. R., Ang K. D., Isaac A. M. L., Joven J. J. R., and Sollano M. B. T., Use of dry mixing method in fly ash based geopolymer as a stabilizer for dredged soil, GEOMATE Journal, vol. 16, no. 57, 2019, pp. 9-14.

[27] Pourakbar S., Asadi A., Huat B. B., Cristelo N., and Fasihnikoutalab M. H., Application of alkali-activated agro-waste reinforced with wollastonite fibers in soil stabilization, Journal of Materials in Civil Engineering, vol. 29, no. 2, 2017, p. 04016206.

[28] Liu Z., Cai C., Liu F., and Fan F., Feasibility study of loess stabilization with fly ash–based geopolymer, Journal of Materials in Civil Engineering, vol. 28, no. 5, 2016, p. 04016003.

[29] Lăzărescu A., Szilagyi H., Ioani A., and Baeră C., Parameters Affecting the Mechanical Properties of Fly Ash-Based Geopolymer Binders–Experimental Results, in IOP Conference Series: Materials Science and Engineering, vol. 374, no. 1: IOP Publishing, 2018, p. 012035.

[30] Reddy S. R. K and Murugan S.B., Experimental and microstructural assessment of ternary blended geopolymer concrete with different Na2SiO3-to-NaOH volume ratios, Innovative Infrastructure Solutions, vol. 5, no. 1, 2020, p. 33.

[31] Santhikala R., Chandramouli K., and Pannirselvam N., Stabilization of expansive soil using flyash based geopolymer, Materials Today: Proceedings, vol. 68, 2022, pp. 110-114.

[32] Noaman M.F., Khan M., Ali K., and Hassan A., A review on the effect of fly ash on the geotechnical properties and stability of soil, Cleaner Materials, 2022, p. 100151.

[33] Varma N., Kumar T., and Nagaraju V., Compressive Strength of High Plastic Clay Stabilized with Fly Ash-Based Geopolymer and Its Synthesis Parameters, in Transportation, Water and Environmental Geotechnics: Proceedings of Indian Geotechnical Conference In 2020, India, vol. 4, Springer Singapore, 2021, pp. 25-37.

[34] Turan C., Javadi A.A., and Vinai R., Effects of class C and class F fly ash on mechanical and microstructural behavior of clay soil—a comparative study, Materials, vol. 15, no. 5, 2022, p. 1845.

[35] Abdullah H.H., Shahin M. A., and Walske M.L., Review of fly-ash-based geopolymers for

soil stabilisation with special reference to clay, Geosciences, vol. 10, no. 7, 2020, p. 249.

[36] Kwad N. F., Abdulkareem A. H., and Ahmed T. M., The effect of fly ash based geopolymer on the strength of problematic subgrade soil with high CaO content, in Proceedings of the 9th International Conference on Maintenance and Rehabilitation of Pavements—Mairepav9, Springer, 2020, pp. 539-551.

[37] Malikzada A., Pulat H. F., and Develioğlu I., Effect of Fly Ash on Compaction Behavior of Alluvial Soil, in 5th International Students Science Congress Proceedings Book, 2021, pp. 126-135.

[38] Karim H. H., Samueel Z. W., and Jassem A. H., Influence of fly ash addition on behavior of soft clayey soil, Engineering and Technology Journal, vol. 38, no. 5, 2020, pp. 698-706.

[39] Deepak M., Rohini S., Harini B., and Ananthi G. B. G., Influence of fly-ash on the engineering characteristics of stabilised clay soil, Materials today: proceedings, vol. 37, 2021, pp. 2014-2018.

[40] Kumar M., Singh J. P., and Mishra M. K., An Experimental Study of Soil Stabilisation Using Sodium Hydroxide Additive, International Journal of Research and Innovation in Applied Science, vol. III, no. V, 2018, pp. 7-11.

[41] Nagaraj V. K., and Babu D. V., Assessing the performance of molarity and alkaline activator ratio on engineering properties of self-compacting alkaline activated concrete at ambient temperature, Journal of Building Engineering, vol. 20, 2018, pp. 137-155.

[42] Diana W., Hartono E., Pratama W.E., and Wardani W.I., Shear strength characteristic of geopolymer fly ash and egg shell powder stabilized clay soil, in E3S Web of Conferences, vol. 429: EDP Sciences, 2023, pp. 1-6.

[43] Hartono E., Diana W., and Hendriana J. W., Study of compressive strength and durability of geopolymer stabilized clay shale with fly ash binder and 12M NaOH content, in AIP Conference Proceedings, vol. 2846, no. 1: AIP Publishing, 2023,p. 04025.

[44] ASTM, D 698–2000 Test Method for Laboratory Compaction Characteristics of Soils Using Standard Effort, Annual Book of ASTM Standards, vol. 4, 2000.

[45] Santos F., Li L., Li Y., and Amini F., Geotechnical properties of fly ash and soil mixtures for use in highway embankments, in World of Coal Ash (WOCA) Conference, May, vol. 9, 2011, p. 12.

[46] Gu L., Lv Q., Wang S., Xiang J., Guo L., and Jiang J., Effect of sodium silicate on the properties of loess stabilized with alkali-activated fly ash-based, Construction and Building Materials, vol. 280, 2021, p. 122515.

[47] Alavi A., Gandomi A., Gandomi M., and Hosseini S.S., Prediction of maximum dry density and optimum moisture content of stabilised soil using RBF neural networks, The IES Journal Part A: Civil & Structural Engineering, vol. 2, no. 2, 2009, pp. 98-106.